High-Energy Gamma-Astronomy with Milagro

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Introduction

High-energy gamma-ray astronomy probes nonthermal, energetic acceleration processes in the Universe. The list of known gamma-ray sources includes active galaxies, supernova remnants, and gamma-ray bursters (GRBs). Gamma rays are also produced when high-energy cosmic rays interact with matter in the Galaxy. Other potential sources include more exotic objects such as evaporating primordial black holes, topological defects, and dark-matter particle annihilation and decay.

Cosmic gamma rays up to 10–100 GeV can be directly detected with satellite-based detectors, such as EGRET[1] (now defunct) and GLAST[2] (currently under construction). EGRET observed a number of point gamma-ray sources as well as the diffuse emission of gamma rays from the galactic plane. Approximately 170 of the EGRET sources have not been identified with known astronomical objects, and so warrant further study. GLAST, presently scheduled for a launch in 2005, will extend and improve these measurements.

At higher energies, the gamma-ray flux from even the brightest source is too low to be measured with the relatively small detectors that can be placed in satellites; thus Earth-based techniques are used. High-energy gamma rays interact high in the Earth's atmosphere producing a cascade of particles called an extensive air shower (EAS). Ground-based gamma-ray telescopes detect the products of an EAS that survive to ground level, either the Cerenkov light produced in the atmosphere by the shower particles (atmospheric Čerenkov telescopes [ACTs]) or the shower particles (predominantly electrons, positrons, and gamma rays) that reach ground level (extensive air shower arrays [EAS arrays]).

After many years of perfecting the technique, ACTs have been successfully employed to detect very-high-energy gamma rays (VHE, ≈400 GeV–10 TeV) from several sources including three plerions (a system like the Crab, in which a young pulsar powers a compact nebula via synchrotron emission and inverse Compton scattering), at least three active galaxies, and one supernova remnant. These observations have greatly expanded our understanding of the acceleration mechanisms at work in these objects. EAS arrays, including the CYGNUS array in Los Alamos (now dismantled), use widely spaced scintillation counters to search for gamma-ray sources above ≈40 TeV. No convincing evidence for gamma-ray emission from any source has been obtained with EAS arrays in this energy region.

While ACTs have excellent angular resolution and sensitivity, they can only be used on clear, dark nights and can only view one source at a time (and only during that part of the year when that source is in the night sky). Thus they are not well suited to perform an all-sky survey, to monitor a known source for episodic emission, or to search for the emission of gamma rays from a source at an unknown direction and/or time (such as from a GRB).

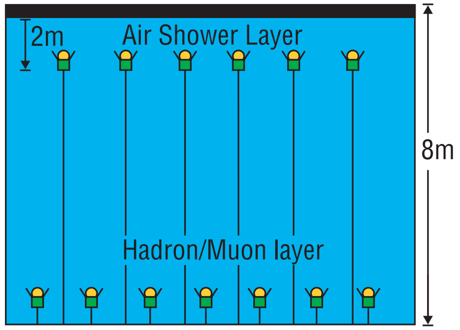

Figure 1. A schematic diagram of Milagro showing the two layers of photomultiplier tubes (PMTs) deployed in the water.

By contrast, an EAS array can operate 24 hours per day, regardless of weather, and can observe the entire overhead sky. The trick is to build an EAS array with a significantly lower energy threshold to overlap the energy regime studied with ACTs, where gamma-ray sources are known to exist.

The energy threshold of an EAS array is determined by the fraction of the shower particles reaching the ground that are detected and by the altitude of the detector (more shower particles survive at high altitudes so the energy threshold is lower). Milagro achieves a low energy threshold by employing photomultiplier tubes (PMTs) installed in a large, high-altitude, covered pond of water. The charged shower particles emit Čerenkov radiation when they traverse the water, which is detected by the PMTs: gamma rays in the shower convert in the water to electron-positron pairs, which in turn emit Čerenkov radiation and are detected. Figure 1 shows a schematic diagram of Milagro. Milagro is the first continuously operating, large-solid-angle detector sensitive to cosmic gamma rays below 1 TeV.

Milagro Project Summary

Milagro has been built in an existing man-made 5,000,000-gallon pond of water at Fenton Hill, ≈35 miles west of Los Alamos. Fenton Hill, at an altitude of 2650 meters above sea level (an atmospheric depth of 750 g/cm^2), is a technical area (TA-57) of Los Alamos National Laboratory (the Laboratory) leased from the US Forest Service for the purpose of performing fundamental geothermal research. When the geothermal project ended, the Milagro collaboration was able to take over the pond for gamma-ray astronomy. Figure 2 shows an aerial view of the Milagro pond. To construct Milagro, the collaboration spent several years on a number of tasks, including:

- emptying and cleaning the pond;
- installing a new polypropylene liner in and cover over the pond;
- constructing a utility building to house a water recirculation and purification system and fans to inflate the cover (to allow the installation of the detector elements in the pond);
- setting up an electronics trailer;
- installing electric power and communications (a T1 line);
- testing the PMTs;
- building electronics and a data-acquisition system; and
- installing the PMTs and cabling in the pond and connecting them to the electronics.

In 1996 a prototype detector called Milagrito[3], consisting of 225 8" PMTs tethered to a grid of sand-filled PVC pipe on the bottom of the pond, was installed. The pond was filled with water to a level 1 m above the PMTs, and in February 1997 data collection began. Milagrito gathered data until May 1998, at which time it was dismantled to allow the full Milagro detector to be installed. In addition to obtaining some notable results (see below), the experience with Milagrito led to some important changes in the detector design including the implementation of conical "baffles" on each PMT, which are reflecting on top to increase the effective area of the PMT and black on the bottom to absorb stray light.

The construction of the central Milagro detector, which has 723 PMTs in two layers and 8 m of water, was completed in late 1998, followed by a series of engineering runs. The bottom layer is used to reject showers initiated by background charged cosmic-rays. Data-taking began in late 1999 and the collaboration is now embarking upon an ambitious program of

Figure 2. An aerial view of the Milagro pond. In this photograph, the cover is inflated to allow construction activities inside the pond. The buildings beyond the pond house the water recirculation and purification system, the electronics, and the data analysis computers.

data collection and physics analysis.

A small team of Laboratory scientists has played a leading role in all aspects of the Milagro project from its inception, including design, construction, operation, and physics research. An array of 150 “outrigger” detectors, each an 8'-diameter tank of water with a PMT, is now being deployed in the 10 acres that surround the pond; the outriggers will greatly improve the sensitivity of Milagro to gamma-ray sources.

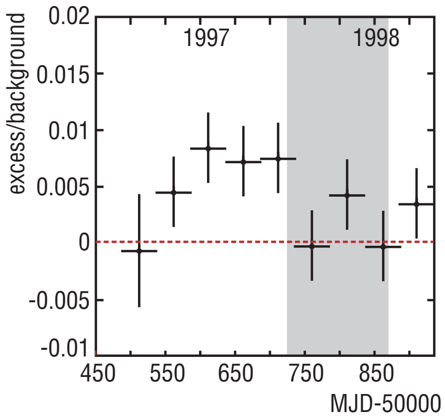

Figure 3. The fractional event excess observed with Milagrito for 50-day periods from Markarian 501 as a function of time. The shaded area indicates the period for which the source is in the daytime sky and is not observable with air Čerenkov telescopes.

Milagro Detector Results

Milagro is the first gamma-ray detector that can continuously monitor the entire overhead sky at energies as low as a few hundred GeV. Milagro is the ideal instrument to study the transient and variable sources (such as GRBs and active galactic nuclei) of VHE gamma rays in the universe and to discover new gamma-ray sources. Results from Milagrito include:

- The detection of TeV emission from Markarian501, an active galaxy[4]. Markarian501 was in an active flaring state in 1997. Milagrito was the only detector to study Markarian501 in winter 1997–98 when it is in the daytime sky (Figure 3). It appears that the flare ended in late 1997.
- The apparent detection of TeV emission from a gamma-ray burst (GRB 970417a)[5]. If this result is confirmed, it is the highest energy emission ever observed from a GRB, and would place severe constraints on models of the mechanism responsible for GRBs. The distribution of the observed events on the sky are shown in Figure 4. The probability that this observation is a fluctuation of the background is quite small (1.5×10^{-3}).
- The observation of a solar ground-level event[6]. Figure 5 shows the detection of the November 6, 1997 ground-level solar event by the neutron monitor at Climax, Colorado together with the scaler and trigger rates from Milagrito. A preliminary analysis indicates that Milagrito detected particles in excess of 10 GeV.

While Milagro only recently began taking data and data-analysis algorithms are still being developed, an early analysis of the first eight months of data from indicates that emission from the Crab has been observed and that the lower PMT layer is effective at rejecting background events.

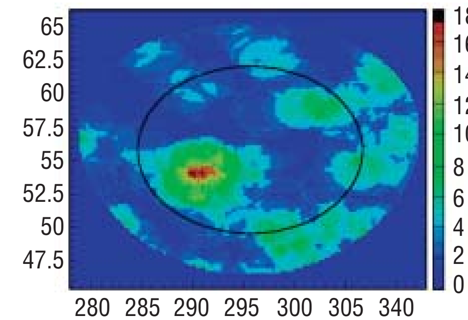

Figure 4: The number of events observed by Milagrito in 1.6°-radius bins in the vicinity of GRB 970417a for the 7.9 s of the burst. The plot encompasses the location and its error as determined by BATSE. The best location determined by Milagrito is centered at R.A. = 289.9°, δ = 54.0°, and has 18 observed events, with an expected background of 3.46 events.

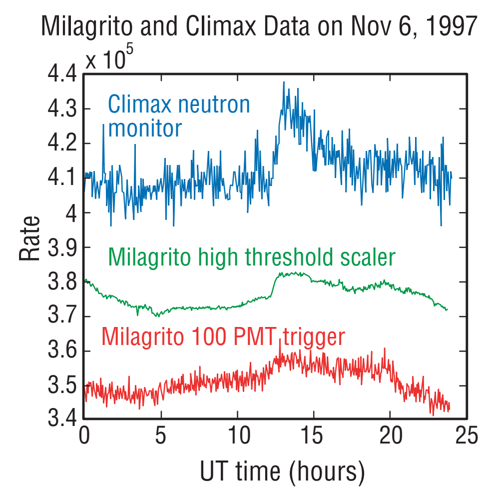

Figure 5: The observed rate from the Climax neutron monitor for the ground-level event of Nov. 6, 1997, together with the total scaler rate and trigger rate from Milagrito.

Importance/Significance of Results

The early results from Milagrito and Milagro have demonstrated that the water-Čerenkov technique works well and that continuous sensitive TeV observations of the sky are possible. While the sensitivity of Milagrito was much poorer than what is being achieved with Milagro, the year-round study of emission from Markarian 501 demonstrates the power of the technique. The observations of GRB970417a and the November 6, 1997 solar flare both represent the highest-energy emission detected from these phenomena and have generated considerable interest within the astrophysics community. The observation of TeV photons from the Crab with Milagro verifies the expected sensitivity of the telescope including the background-rejection capability. The sensitivity of Milagro is being further enhanced by the outrigger detectors, now being installed.

The Milagro collaboration is gratified that years of hard work are now beginning to show results. This new instrument, now shown to work well, should provide many new insights into the high-energy universe.

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For Further Reading

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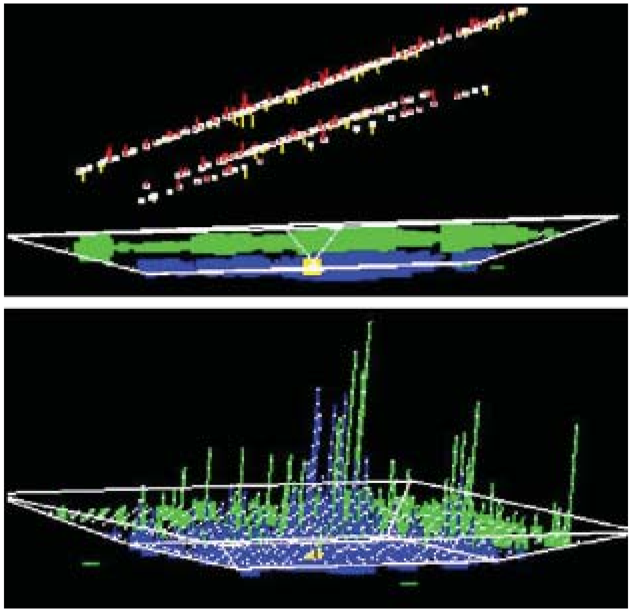

Figure 6. A typical event in Milagro. The upper panel shows fits to the shower plane from the timing of the PMTs (to give the incoming direction): the upper line is for the shower layer and the lower two lines are for the muon layer, whose PMTs are on two different elevations. The bottom panel shows the pulse heights from the shower-layer PMTs (green) and muon-layer PMTs (blue). The location of the shower core is evident in both layers.